# Top Production and Properties at CDF

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Recent top physics results from CDFII at a center-of-mass energy of 1.96 TeV are presented. Besides measurements of the $t\bar{t}$ production cross section in all three decay channels using a set of complementary experimental methods, we report measurements of top branching ratios as well as the $W$ helicity and the search for single top production.

## 1. Introduction

Since the discovery of the top quark [1], experimental attention has turned to the examination of its production and decay properties. In $p\bar{p}$ collisions at the Tevatron top quarks are produced mainly in $t\bar{t}$ pairs, either via quark-antiquark annihilation ($\sim$ 85%) or via gluon-gluon fusion ($\sim$ 15%), with a NLO cross section of $6.7^{+0.7}_{-0.9}$ pb [2] for $M_{top} = 175$ GeV/c$^2$ at the current Tevatron center-of-mass energy of $\sqrt{s} = 1.96$ TeV. In the standard model (SM) the top quark decays almost exclusively into a $W$ boson and a $b$-quark.

Experimentally, we divide the $t\bar{t}$ candidate events by their final states as determined by the decay of the $W$. We classify $t\bar{t}$ events as *dilepton* events if both $W$'s decay leptonically, resulting in $l^+\nu b l^-\bar{\nu}\bar{b}$ final states ($\sim$ 11% of all $t\bar{t}$ events). We classify $t\bar{t}$ events as *lepton+jets* events if one $W$ decays leptonically, and the other $W$ hadronically, resulting in $l^+\nu b q\bar{q}'\bar{b}$ final states ($\sim$ 44%). Finally, we classify $t\bar{t}$ events as *all-hadronic* events if both $W$'s decay hadronically, resulting in $q\bar{q}'bq\bar{q}'\bar{b}$ final states ($\sim$ 44%).

## 2. $t\bar{t}$ Production Cross Section

At CDF [3] we measure the $t\bar{t}$ production cross section in all three categories (*dileptons, lepton+jets, all-hadronic*) using either counting experiments or by fitting the data to kinematic distributions that can discriminate between signal and background.

### 2.1. Dilepton Channel

In the *dilepton* channel we use currently three different methods to measure the cross section in events with two high-momentum, opposite sign leptons, two or more jets and large $\not{E}_T$ [1] due to two escaping neutrinos. The first method is a counting experiment similar to what was used in RunI, that selects two well identified isolated, high-$P_T$ electrons or muons in the combinations $ee$, $\mu\mu$ and $e\mu$. In the second analysis we apply looser lepton identification criteria on the second lepton by asking only for an isolated high-$P_T$ track. This way we gain on overall acceptance as well as on acceptance for $\tau$ leptons in the final state via their one-prong hadronic decay. In both methods we count background subtracted signal candidate events in 197 pb$^{-1}$ of data and correct these for detector acceptance and reconstruction efficiencies to measure the $t\bar{t}$ production cross section [4]. The combined cross section from both methods results in

$$\sigma = 7.0^{+2.4}_{-2.1}(\text{stat})^{+1.6}_{-1.1}(\text{syst}) \pm 0.4(\text{lum})\ \text{pb}. \quad (1)$$

In the third method we take advantage of the different kinematic behaviour of $t\bar{t}$ events with respect to other SM processes, and we perform a si-

[1]We use a cylindrical coordinate system about the beam axis in which $\theta$ is the polar angle, $\phi$ is the azimuthal angle, and pseudorapidity is defined as $\eta = -ln\ tan(\theta/2)$. We define $E_T = E\ sin\theta$ and $P_T = P\ sin\theta$, where $E$ is energy measured by the calorimeter and $P$ is momentum measured by the spectrometer. The missing transverse energy vector, $\not{E}_T$ , is $-\Sigma_i E^i_T n_i$, where $n_i$ is the unit vector in the azimuthal plane that points from the beamline to the $i$th calorimeter tower.

multaneous fit of the data to expected kinematic shapes from signal and background templates in the two-dimensional space of $\not\!\!E_T$ and jet multiplicity. In this fit we treat $t\bar{t}$, $WW$ and $Z \to \tau\tau$ as three distinct signal processes and $WZ$, $ZZ$, $Z \to ee$ and $Z \to \mu\mu$ as one combined background shape. The result of this fit using 197 pb$^{-1}$ of data, yields a $t\bar{t}$ production cross section of

$$\sigma = 8.6^{+2.5}_{-2.4}(\text{stat}) \pm 1.1(\text{syst}) \pm 0.5(\text{lum}) \text{ pb.} \quad (2)$$

All three methods are still statistics limited, and even the dominating systematic uncertainties will improve significantly with higher statistics.

Furthermore, a first look into $t\bar{t}$ *dilepton* events, where one of the $W$ decayed into $e\nu_e$ or $\mu\nu_\mu$ and the other $W$ decayed into $\tau\nu_\tau$, lets us observe 2 events in 197 pb$^{-1}$ of data, when 1.1 $t\bar{t}$ and 1.3 background events are expected. We use this ratio of observed to expected $e\tau$ or $\mu\tau$ events to extract the following limit:

$$\frac{BR(t \to b\tau\nu_\tau)}{BR_{SM}(t \to b\tau\nu_\tau)} < 5.0 \quad @\ 95\%\ CL \quad (3)$$

### 2.2. Lepton+Jets Channel

This was the main channel for the discovery of the top quark in 1995. The large branching ratio of $WW \to \ell\nu + q\bar{q} + b\bar{b}$ together with an efficient trigger due to the high-$P_T$ charged lepton leads to a relatively clean and large $t\bar{t}$ sample, where the main background is from QCD $W$+$jets$ events. For most of the measurements presented here, efficient and pure tagging of jets that originate from $b$-quarks is crucial. Currently, we use two different $b$-tagging algorithms. The first one reconstructs a displaced, secondary vertex with help of the silicon detector (*SVXtagger*), while the second method reconstructs low-$P_T$ muons from semi-leptonic $b$-dacays (*SMUtagger*).

#### 2.2.1. Counting Experiments

Selecting $e$+$jets$ and $\mu$+$jets$ events with three or more jets, where at least one of the jets is tagged as a $b$-jet by the *SVXtagger*, the measured cross section from 162 pb$^{-1}$ of data is

$$\sigma = 5.6^{+1.2}_{-1.1}(\text{stat})^{+1.0}_{-0.7}(\text{syst}) \pm 0.3(\text{lum}) \text{ pb.} \quad (4)$$

If we use the *SMUtagger* instead of the *SVXtagger* we get the following result for the $t\bar{t}$ cross section using 126 pb$^{-1}$ of data:

$$\sigma = 4.1^{+4.0}_{-2.8}(\text{stat}) \pm 1.9(\text{syst}) \pm 0.2(\text{lum}) \text{ pb.} \quad (5)$$

Both methods are statistics limited. The dominating systematic uncertainty is due to the knowledge of the jet energy scale in the calorimeter, which will improve with a more accurate detector simulation and a larger data sample.

#### 2.2.2. Kinematic Fits

Instead of counting signal and background events, one can extract the fraction of $t\bar{t}$ events in the lepton+jets sample by fitting one or more kinematic variables in the data to the expected shapes from signal and backgrounds. We present three different methods using this technique.

In the first method we use the discriminating power of a variable called $H_T$, which is the scalar sum of the transverse energies in the event, namely those of the charged lepton, the neutrino and the three or more jets. Note, that no $b$-tagging is required in this analysis. The resulting cross section in 195 pb$^{-1}$ of data is:

$$\sigma = 4.7 \pm 1.6(\text{stat}) \pm 1.8(\text{syst}) \pm 0.3(\text{lum}) \text{ pb.} \quad (6)$$

The second method is based on the same event selection as the first, but uses a neural net that was trained with seven kinematic variables, to extract the $t\bar{t}$ fraction in the data, resulting in a cross section of

$$\sigma = 6.7 \pm 1.1(\text{stat}) \pm 1.6(\text{syst}) \pm 0.4(\text{lum}) \text{ pb.} \quad (7)$$

Both measurements are already systematics limited, where the dominant systematic uncertainty again comes from the knowledge of the jet energy scale in the calorimeter.

In a third method we use the lepton+jets sample with three or more jets of which at least one was tagged with the *SVXtagger*. We then fit the selected data events to signal and background templates in one kinematic variable, namely the $E_T$ of the highest-$E_T$ jet in the event. This method uses 162 pb$^{-1}$ of data and yields a cross section of

$$\sigma = 6.0^{+1.5}_{-1.8}(\text{stat}) \pm 0.8(\text{syst}) \pm 0.4(\text{lum}) \text{ pb.} \quad (8)$$

This result is still statistics limited with a rather small systematic uncertainty.

### 2.3. All-Hadronic Channel

This is a very challenging channel, since there is no high-$P_T$ lepton in the event that would provide an efficient trigger, and since the six-jet final state allows for a huge background from multi-jet QCD events. Nevertheless, this channel was already part of the 1995 discovery in CDF. We collect the data with a dedicated multi-jet trigger and improve the poor signal-to-background ratio by topological cuts and a cut on the total energy in the event. After asking for at least one of the jets in the event to be tagged as a $b$-jet, one can count signal and expected background events with six to eight jets. The extracted cross section from 165 pb$^{-1}$ of data is

$$\sigma = 7.8^{+2.5}_{-1.0}(\text{stat})^{+4.7}_{-2.3}(\text{syst}) \pm 0.5(\text{lum})\ \text{pb}. \qquad (9)$$

This measurement is limited by the uncertainties on the jet energy scale in the calorimeter.

### 2.4. Cross Section Summary

Fig. 1 summarizes all CDFII $t\bar{t}$ cross section measurements. They are consistent with each other, as well as with results from RunI, with measurements from D0 and with NLO calculations.

## 3. Branching Ratios

In order to measure whether the top quark decays to 100% into $Wb$, or whether it sometimes decays into a lighter quark ($t \to Wq$), we measure the ratio of branching ratios $R = \frac{BR(t\to Wb)}{BR(t\to Wq)}$, where $q$ denotes a $d, s$ or $b$-quark. Assuming three-generation CKM unitarity, $R > 0.998$ is expected. We measure $R$ by measuring the $b$-quark content in the selected $t\bar{t}$ samples. By measuring the 0-, 1- and 2-tag rates in various samples, i.e. *dilepton*, *lepton+jets* with three jets, *lepton+jets* with four or more jets, we can determine $R$ from a combined likelihood for predicted and observed events. In 161 pb$^{-1}$ of data we measure

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = 1.11^{+0.21}_{-0.19} \qquad (10)$$

in good agreement with the SM expectation. We then extract a lower limit for $R$ within the Feldman-Cousins framework [5] to be:

$$R > 0.62 \quad @ \quad 95\%\ CL. \qquad (11)$$

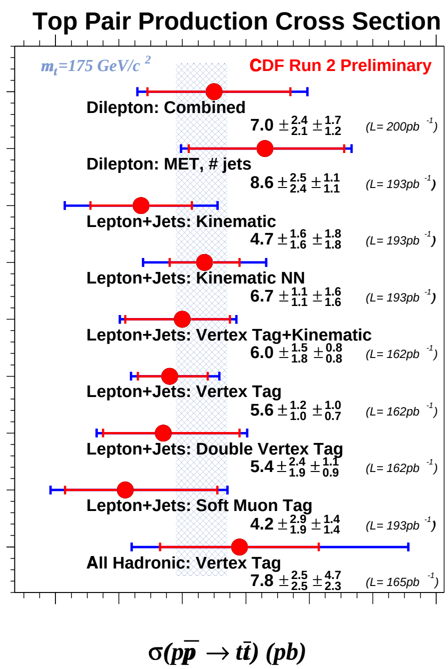


Figure 1. Compilation of measured $t\bar{t}$ cross sections from CDFII. The band is the theory expectation [2].

On the other hand, if we allow for the top quark to decay into something that does not include a $W$ boson, like $t \to Xb$, where $X \to qq'$, or $t \to Yb$, where $Y \to \ell\nu$, then the *dilepton* and *lepton+jets* cross sections would disagree. In order to test this hypothesis, we measure the ratio of cross sections: $R_\sigma = \frac{\sigma_{dilepton}}{\sigma_{lepton+jets}}$. The result from the first 125 pb$^{-1}$ of data is:

$$R_\sigma = 1.45^{+0.83}_{-0.55}. \qquad (12)$$

Within the large uncertainty, this is in agreement with the SM expectation of $R = 1$.

## 4. W Helicity

In the SM, the $W$ boson couples only to left-handed particles (or right-handed anti-particles). Together with angular momentum conservation, this allows the top quark to decay only into left-handed (negative-helicity) or longitudinally polarized (0-helicity) $W$ bosons. In the SM the fraction of longitudinally polarized $W$ is given by $F_0 = \frac{1}{1+2(m_W/m_t)^2} \approx 0.70$. By measuring $F_0$ we test the $V-A$ structure of the weak interaction at high energy. The helicity of the $W$ manifests itself in decay product kinematics, such as the $P_T$ or the angular distribution of the charged lepton from the $W$ decay.

Analysing both, *dilepton* as well as *lepton+jets* events, we fit the charged lepton ($e$ or $\mu$) $P_T$ spectrum for the fraction of longitudinally polarized $W$ bosons. In about 200 pb$^{-1}$ of data we measure

$$F_0 = 0.27^{+0.35}_{-0.24} \tag{13}$$

in the combined sample. In the *dilepton* sample we observe an excess of events at low lepton $P_T$, which pulls the combined result down towards low values of $F_0$. If we perform the fit to the *lepton+jets* sample alone, the fit yields $F_0 = 0.88^{+0.12}_{-0.47}$. Both results are in agreement with the SM expectation of 0.70.

## 5. Single Top

At a rate of about 40% of the pair production process, top quarks should be produced as single top via electroweak production. In the SM it can be produced in $p\bar{p}$ collisions either in the $s$-channel at a cross section of $0.88 \pm 0.11$ pb, or in the $t$-channel at $1.98 \pm 0.24$ pb [6]. The measurement of single top production gives us direct access to $|V_{tb}|^2$ and sensitivity to new physics, particularly, in the $s$-channel, to the production of new charged gauge bosons, and in the $t$-channel to anomalous couplings and flavour changing neutral currents. We perform a search for single top production in events with a $W$ and exactly two jets, out of which at least one is tagged as a $b$-jet by the *SVXtagger*.

We perform two separate searches in 162 pb$^{-1}$ of data, one for the combined $s$- and $t$-channel process and one in the $t$-channel only. For the combined search we perform a likelihood fit to the $H_T$ distribution (scalar sum of the transverse energy of all objects in the event) of the data, assuming the shapes for single top, $t\bar{t}$ and non-top backgrounds from monte carlo simulations. In case of the $t$-channel search we perform a fit to $Q_\ell \times \eta_q$, where $Q_\ell$ is the charge of the charged lepton from the $W$ decay, and $\eta_q$ is the pseudo-rapidity of the untagged jet.

No significant contribution from single top production is observed. The fits result in the following upper limits:

$$\sigma(t-channel) < 10.1\,pb \quad @ \quad 95\%\ CL, \tag{14}$$
$$\sigma(s-channel) < 13.6\,pb \quad @ \quad 95\%\ CL, \tag{15}$$
$$\sigma(combined) < 17.8\,pb \quad @ \quad 95\%\ CL. \tag{16}$$
$$\tag{17}$$

It should be noted that, following the discovery of single top production, the expected precision for single top measurements in CDFII for 2 fb$^{-1}$ is: $\delta\sigma(tbX) = 26\%$, $\delta\Gamma(t \to Wb) = 28\%$ and $\delta|V_{tb}| = 14\%$.

## 6. Summary and Conclusions

The measurements we present here, re-establish the top quark in RunII in CDF. Increased beam energies and detector coverage, as well as refined analysis methods, will allow soon for precision measurements in the top sector, and therefore for a better understanding of electroweak symmetry breaking.

## REFERENCES


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